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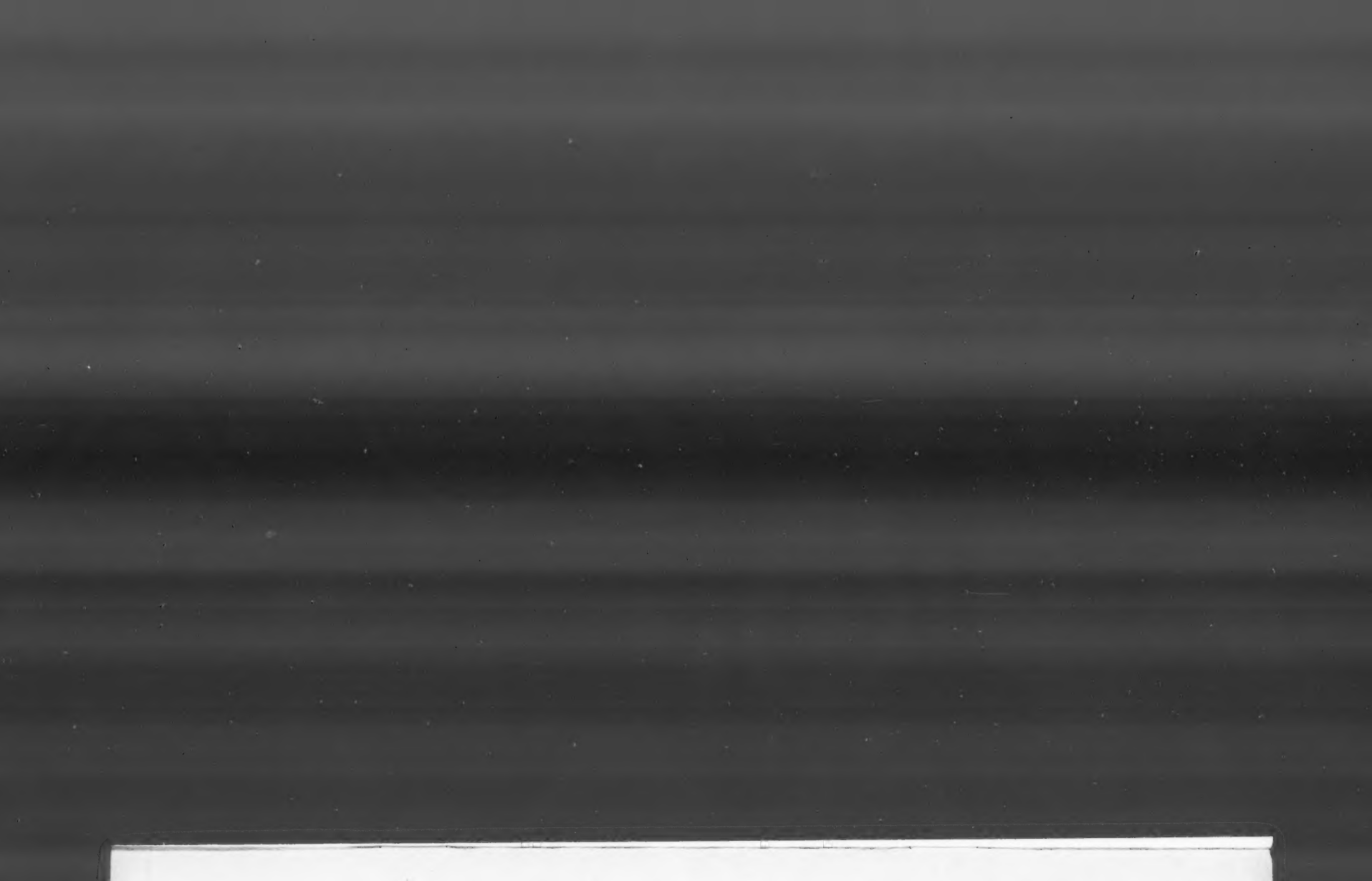

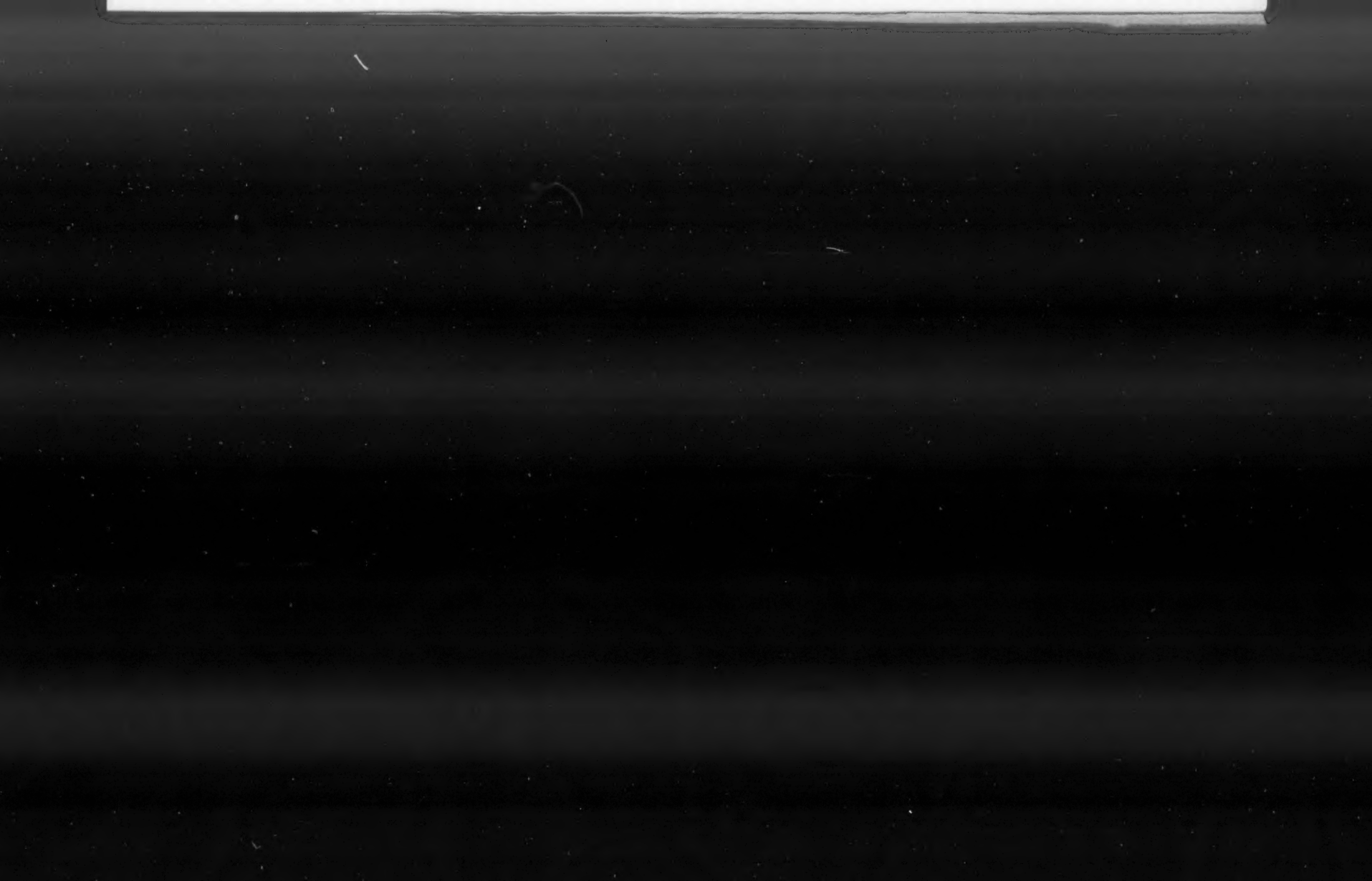

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ON MICROWAVE CONDUCTIVITY, NOISE, AND OSCILLATION OF GAS DISCHARGE PLASMA

PAAVO JÄÄSKELÄINEN

HELSINKI 1960

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INTRODUCTION

Elucidation of the properties of gas discharge plasma with the aid of microwave measurements is primarily based on the theoretical results of the work concerning cavities done by Slater [1] and that concerning plasma conductivity by Margenau [2]. Adler [3] carried out microwave conductivity measurements by placing the discharge tube in a simple cavity; Rose and Brown [4] presented a number of microwave measuring methods for physical research, and Mumford [5] was the first to utilize the noise radiated by the positive column in the discharge tube. The present article deals with discharge tubes for use as sources of noise in radio techniques. The electron density is so high in these tubes that the plasma can no longer be considered a poorly conducting medium at the frequencies employed in the experiments, which are of the order of magnitude 1200 Mc. Moreover, these frequencies are lower than the electron plasma frequency, and the plasma tends to insulate its interior from the electromagnetic field [6]. A discharge tube with gas filling identical to that in fluorescent lamps was used in the present experiments.

1. FUNDAMENTAL FORMULAE

At first, some basic relationships concerning the microwave conductivity and noise of gas discharge plasma required for the treatment of the experimental results shall be presented, mainly in accordance with Margenau [2,7] and Van der Ziel [8].

The effect of gas ionization can be formally accounted for by writing either the conductivity σ or the dielectric constant ε as a complex quantity. Gas discharges are usually treated using the complex conductivity

$$\sigma = \sigma_r + j\sigma_i = \frac{4\pi}{3}\frac{ne^2}{m}\int_0^\infty \frac{1}{\nu + j\omega}\frac{\partial f_o(v)}{\partial v} v^3 dv \qquad (1)$$

where

n	electron density,
e	charge of the electron,
m	mass of the electron,
ν	collision frequency,
$f_o(v)$	velocity distribution of the electrons,
v	electron velocity,
$\omega = 2\pi f$	angular frequency of the microwave field.

When the electron velocities conform to Maxwell's distribution and the collision frequency ν is assumed to be independent of velocity v, the plasma conductivity

assumes the Lorentz form

$$\sigma = \frac{ne^2}{m}\left(\frac{\nu}{\nu^2 + \omega^2} - j\frac{\omega}{\nu^2 + \omega^2}\right) \tag{2}$$

This formula is simple and useful as an orientative formula, but it always is not adequate for elucidation of the properties of the discharge plasma with the aid of microwaves. Such considerations have to be based on the result derived by Margenau [2]:

$$\sigma = \frac{4\ ne^2 l}{3\sqrt{2\pi mkT_e}}\left[K_2(x_1) - j\sqrt{x_1}\ K_{3/2}(x_1)\right] \tag{3}$$

where

$$K_\varrho(x_1) = \int_0^\infty \frac{x^\varrho\ e^{-x}}{x_1 + x}\,dx$$

$$x_1 = \frac{m(\omega l)^2}{2kT_e}$$

l	mean free path of the electron,
k	Boltzmann's constant,
T_e	the electron temperature.

Margenau's conductivity formula is based on the premises that Maxwell's velocity distribution applies and that the mean free path l is independent of the velocity v. At a given frequency, the real part of the conductivity attains a maximum for $x_1 = 2.1$; the mean free time of the electron is then approximately $1/\omega$. The imaginary part is a monotonically increasing function of x_1.

The problem of determining the noise of thermal origin radiated by the discharge plasma reverts to application of the radiation laws for a black body. According to Planck, the density of radiant energy emitted by a black body is

$$\frac{8\pi hf^3}{c^3}\, g(f)\, df \tag{4}$$

where

c velocity of light,
h Planck's constant,

$$g(f) = \frac{1}{e^{\frac{hf}{kT}} - 1}$$

The noise output obtainable from a black body is, according to Nyquist's thermodynamic considerations,

$$P(f) = hfg(f)\, df \tag{5}$$

When a perfectly reflecting cavity contains particles having velocities which conform to Maxwell's distribution, the density of the radiant energy conforms to the law (4) in this case, too, according to Einstein (cf. Bergmann [9]). In particular, if discharge plasma has been inserted in the cavity, the electrons (being highly mobile owing to their small mass) determine the radiation, and the electron temperature has to be used in the g(f) term. Accordingly, the obtainable thermal noise can be determined by the relationship (5), using the electron temperature.

The relationship between the electron temperature in the positive column of the gas discharge tube and the other parameters of the discharge tube can be implicitely presented in the following manner [10; p. 239]:

$$\frac{1}{\sqrt{\frac{eV_i}{kT_e}}}\, e^{\frac{eV_i}{kT_e}} = (CpR)^2 1,16 \times 10^7 \tag{6}$$

where

V_i	ionization potential,
C	a characteristic constant of the gas,
p	pressure, in mm Hg,
R	inner radius of the tube.

This relationship derived by Von Engel and Steenbeck is based on Maxwell's velocity distribution and ambipolar diffusion.

2. MICROWAVE NOISE OF THE DISCHARGE PLASMA

The effect of the dependency of the noise on frequency, $g(f)$, is not perceptible until the infra-red range. In the microwave range, one may write

$$\frac{hf}{kT_e} \ll 1 \tag{7}$$

and the basic noise equation (5) assumes the form

$$P = kT_e\, df \tag{8}$$

The foregoing is based on thermodynamic considerations and has reference only to thermal noise. The noise of a gas discharge can also be treated by means of the kinetic theory. However, no additional light is thrown on the question if only random motions are taken into account. Parzen and Goldstein [11] have treated direct current discharges and they have also accounted for the drift of the electrons in the D.C. field, their result being:

$$P(f) = kT_e\, df + \frac{P_o\, \tau_o}{N} (\cos^2\theta) \left[1 + \frac{2}{1 + (\omega\tau_o)^2} \right] df \tag{9}$$

where

P_o	D.C. power of the discharge tube,
τ_o	mean free time of the electron,
N	average number of electrons in the discharge,
θ	angle between the tube axis and the electric field of the measuring system.

In deducing this result, the quantum effects have been neglected in accordance with (7) and the electron velocities before and after collision have been assumed to be mutually independent. The assumption concerning the velocities is correct when $\omega\tau_o \gg 1$ [8; p. 325]. For fluorescent lamps and for other discharge tubes of similar kind for use as sources of noise in radio techniques, there is $\omega\tau_o \sim 1$ at 30 cm wave length. The expression (9) given by Parzen and Goldstein is therefore valid almost over the entire microwave range. Its first part represents thermal noise, the latter part representing shot noise. The contribution of shot noise amounts to a few per cent at the most, also when $\theta = 0$, and it is usually below measurable magnitude.

On the strength of the foregoing, the noise radiated by discharge tubes used as sources of noise in radio techniques is dependent on frequency only for waves shorter than microwaves (quantum effects) and longer than microwaves (shot noise). For all practical purposes the noise in the entire microwave range has thermal origin and the noise temperature thus equals the electron temperature. The electron temperature, in turn, may be calculated in the manner shown by Von Engel and Steenbeck (6), or it may be measured with the aid of probes or by microwave methods. However, the electron temperature of a completely unknown discharge tube cannot be found with the aid of conductivity determinations alone, as only n and $1^2/T_e$ can be thus determined, according to Margenau (3).

3. EXPERIMENTAL DISCHARGE TUBE SET-UP

In the present experiments a discharge tube of 2 cm diameter and with 12 cm electrode spacing was used. Mere activated filaments served as anode and cathode. When the operating point of a tube of this kind lies in the glow discharge range, the potential drops at the electrodes total about 20 volts and the loss of voltage in the positive column is about 1.3 volts per cm. The burning voltage of the tube was thus about 35 volts.

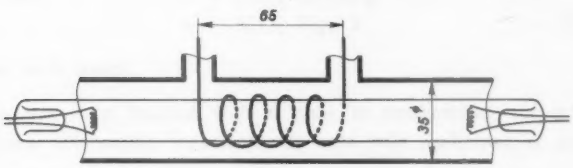


Fig. 1.

For the measurements, the tube was placed in a transmission line. In view of the small length of the positive column a helical design was used [12] for slowing down the electromagnetic wave. Fig. 1 shows a schematic diagram of the discharge tube mount. The measuring frequencies were of the order of 1200 Mc. and they were consequently within the cut-off region of the circular waveguide extending past the ends of the helix.

Two actual structures were designed and they shall be referred to as the loss-free helix line and the helix line with losses in the following. The first-mentioned helix had no separate supporting structure, that is, the circuit was made of metal in its entirety and the losses were negligible. In the latter instance the inner conductor was wound on a pertinax tube, resulting in considerable losses at microwaves.

The impedance of the discharge tube set-up under conditions of gas discharge was adjusted to 50 ohms. This impedance was ultimately achieved experimentally by finding an appropriate pitch of the helix and outer conductor diameter.

4. ATTENUATION MEASUREMENTS

A signal generator with calibrated attenuator and an output meter were used for the measurements. When measuring high attenuations, the output meter indication was kept constant, the attenuation being found by the insertion method as the difference between two readings of the signal generator attenuator. For the measuring of low attenuations the output of the signal generator was kept constant and the attenuation was deduced from the difference of the output meter readings.

Results of the attenuation measurements:

a) Loss-free helix line:

Insertion loss	$A \approx 0$ dB, discharge D.C.	I = 0 mA
	A = A(f), Fig. 2	I = 125 mA.

b) Helix line with losses:

This case was only studied with a view to determining the effective noise temperature. Attenuation measurements were only performed at 1250 Mc.

Insertion loss	A = 3.0 dB, discharge D.C.	I = 0 mA,
	A = 24 dB,	I = 150 mA.

The discharge tube set-up had been matched to the measuring line in all measurements (standing-wave ratio < 1.2). The attenuation values given above are therefore exclusively due to resistive losses.

It is particularly noted that a maximum can be observed in the attenuation curve of the discharge tube set-up in the frequency range studied in this work; Fig. 2. In order to check this observation, a series of further helices with dimensions differing from those of the original helix were made. Subsequent attenuation measurements again revealed the existence of a maximum, which

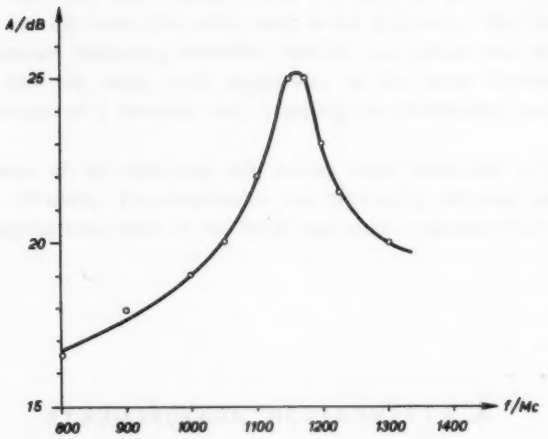


Fig. 2.

occurred in fact always at the same point as with the original structure. Its occurrence is thus not attributable to the circuit, but it is a characteristic of the discharge plasma.

5. EFFECTIVE NOISE TEMPERATURE

If it is desired to use the system shown in Fig. 1 as a device for the measurement of noise, it is necessary to know its noise temperature.

When the discharge plasma produces an attenuation in excess of 15 dB in the helix line and the transition from measuring line to helix line is free of reflection, the system constitutes a load matched to the measuring line. If the helix line itself is free of losses, then, conversely, the plasma noise can pass into the measuring line without impediment. The discharge tube set-up can therefore be likened to a matched load, heated to the electron temperature of the plasma. The noise temperature is thus $T = T_e$ ($= 11400^{\circ}K$ when the temperature of the discharge tube is about $45^{\circ}C$ [5]).

When the system is matched but the transmission line itself has losses, matching is partly obtained trough the effect of the losses in the transmission line. The losses of the line itself are equivalent to a resistance, which is approximately at room temperature. The effective noise temperature will thus obviously be lower than the electron temperature; and if, conversely, we consider the dissipation of the introduced external signal power P in the different parts of the system, it can be seen that the effective noise temperature T is obviously determined by the relationship

$$PT = \sum_i P_i T_i \tag{10}$$

where P_i is the signal power dissipated in a given part of the system and T_i is the noise temperature of this part. The losses of the transmission line are

distributed over its length. It is therefore necessary to determine the noise temperature of a device of the kind referred to under 4)b on the basis of the relationship (10) in accordance with the theory of transmission lines [13]; this procedure gave the result about 0.9 T_e in the present case. Comparison with known sources of noise gave the same result.

6. MEAN FREE PATH OF THE ELECTRON

The helix line employed in the experiments is a periodic structure and its propagation constant would require a highly complicated mathematical representation. As furthermore under the experimental conditions the discharge plasma was equivalent to a semi-conductive medium, the mathematical relationship between the attenuation and the real part of the conductivity is difficult to determine. However, from the physical point of view the interaction between microwaves and plasma in the helix line is similar in character to that in simpler, aperiodic structures, or in fact to that in an unbounded space filled with plasma. We can therefore consider a plane wave.

From the propagation constant of the transverse electromagnetic wave

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma_r + j\omega\varepsilon)} \tag{11}$$

we find for the attenuation factor:

$$\alpha = \omega \sqrt{\pm\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma_r}{\omega\varepsilon}\right)^2} \mp 1\right)} \tag{12}$$

where the upper and lower signs apply when $\varepsilon > 0$ and $\varepsilon < 0$, respectively. For the plasma we may write the permeability $\mu = \mu_0$ and the dielectric constant

$\varepsilon = \varepsilon_0 + \sigma_i/\omega$ (cf. [4]). σ_r and σ_i are functions of x_1 (3), which in its turn is a function of frequency and of the free path. We can infer from the values reported in the literature for the plasma in fluorescent lamps [14] that there was, under the present experimental conditions,

$$\sigma_r \sim 0.5 \frac{1}{\Omega m} \quad \text{and}$$

$$\sigma_i \sim -0.5 \frac{1}{\Omega m} \quad \text{whereof}$$

$$\left(\frac{\sigma_r}{\omega\varepsilon}\right)^2 \sim 1$$

It is seen that the expression (12) of the attenuation cannot be replaced with either one of the simplifications referring to a good or poor conductor.

According to the numerical values reported in the foregoing, there was $\varepsilon \approx \sigma_i/\omega$ under our experimental conditions. With this approximation the expression (12) of the attenuation becomes

$$\alpha = \sqrt{\frac{\mu}{2}\left(\sqrt{(\omega\sigma_i)^2 + (\omega\sigma_r)^2} - \omega\sigma_i\right)} \tag{13}$$

The extreme value considerations carried out by Margenau [2] for the real and imaginary parts of the plasma conductivity with respect to the free path are valid for the functions $\omega\sigma_r$ and $\omega\sigma_i$ with respect to frequency because ω and l appear as homologous variables in these functions (v. (3)).

The attenuation maximum of the helix line occurred at the frequency 1160 Mc. (Fig. 2). If the maximum of the real part of the plasma conductivity coincided with this frequency, which is quite likely, then, according to paragraph 1), the free path has had a value satisfying the condition

$$x_1 = \frac{m(\omega l)^2}{2kT_e} = 2.1$$

Using the electron temperature $T_e = 11400^\circ K$, we find from this condition for the mean free path of the electron: l = 0.012 cm.

7. PLASMA OSCILLATION OBSERVATIONS

Particularly objectionable among the oscillations occurring in discharge tube noise sources are the so-called moving striations. They cause impulse noise and impedance variations of the noise generator. The impedance variation in its turn may affect the properties of the microwave receiver when the noise of the receiver is being measured. It is important for this reason to observe the presence of oscillations in the discharge tube.

The moving striations are a phenomenon inherent in the discharge tube and they cannot be influenced as a rule by means of external circuit arrangements. It has been shown [15] that a stable positive column cannot occur at all if there is a certain ratio between the production and disappearance of ions and metastable atoms. Moving striations imply the existence of an oscillation, which usually has a frequency falling into the audio range. Even if the light intensity of the discharge should become zero in the spaces between the positive stripes, the light column usually registers as a continuous column on the human eye, owing to the considerable velocity of the striations; it is thus impossible to distinguish between oscillating and non-oscillating columns by such visual observation.

Oscillations were observed in a few tubes only and even then only occasionally, mostly immediately after the tube had been ignited. When the tube was oscillating, the oscilloscope revealed a variation of about $\pm$ 3 volts in its burning voltage (about 35 volts). The frequency of this oscillation varied between 6 and 10 kc. in the different instances. It had a curve shape intermediate between sine and saw-tooth waves.

The positive stripes are the result of vigorous ionization at the anode. As a consequence, the glow light filled also the space behind the anode (Fig. 3) in the discharge tubes employed in this work, in which the anode, too, had the shape of a filament (Fig. 1). When the tube is non-oscillating, the glow light appears

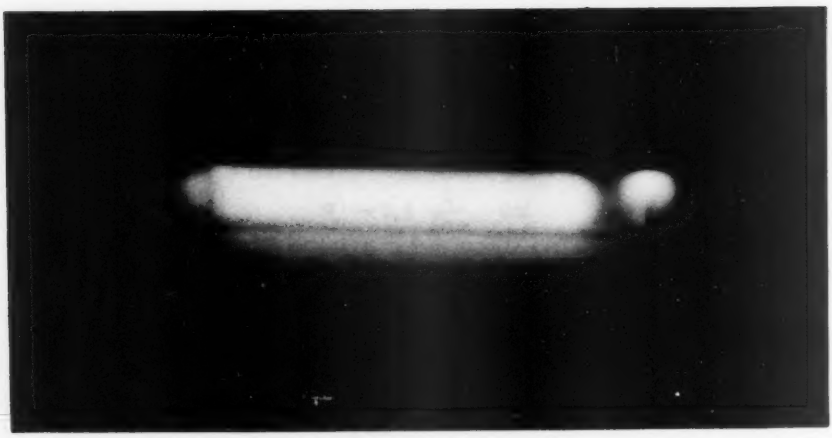


Fig. 3. Oscillating discharge tube.

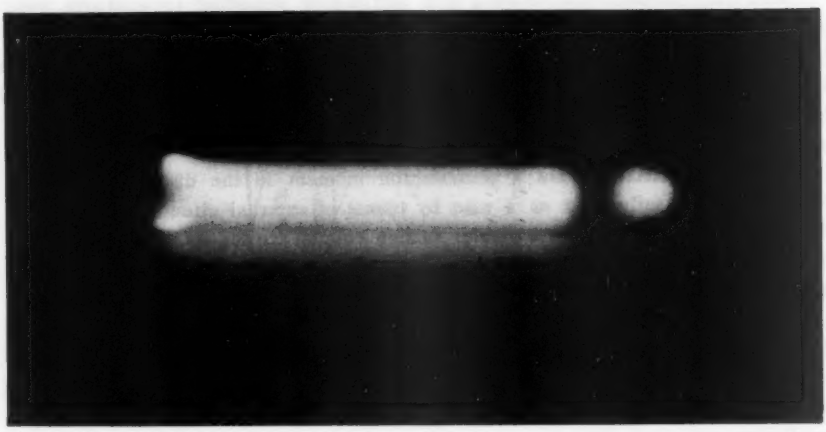


Fig. 4. Non-oscillating discharge tube.

clearly delineated from the anode toward the cathode, Fig. 4. This luminous phenomenon provided a means of observing with the unaided eye whether the tube was oscillating.

SUMMARY

The basic formulae for the microwave conductivity and noise of gas discharge plasma have been presented primarily in accordance with Margenau [2,7] and Van der Ziel [8]. On their basis certain properties of the plasma could be determined by microwave measurements. When Maxwell's velocity distribution is valid, the noise of stable plasma in the microwave range is in its entirety of thermal origin for all practical purposes. Taking into account the losses occurring in the system, the effective noise temperature can be determined from the electron temperature, and vice versa.

Experimental measurements were carried out with a discharge tube having a gas filling identical with that of fluorescent lamps. This tube was placed within a helix line. The electron temperature being known, the effective noise temperature and the mean free path of the electron were determined from attenuation measurements.

In investigations concerning the occurrence of plasma oscillations, a special luminous phenomenon was observed at the anode when there were moving striations. Although the positive column registers as a continuous column on the human eye, the said phenomenon provided a means to notice with the unaided eye whether oscillations were present.

REFERENCES

[1] Slater, J.C.: Rev. Modern Phys. 18 (1946) p. 441.

[2] Margenau, H.: Phys. Rev. 69 (1946) p. 508.

[3] Adler, F.P.: J. Appl. Phys. 20 (1949) p. 1125.

[4] Rose, D., Brown, S.C.: J. Appl. Phys. 23 (1952) p. 1028.

[5] Mumford, W.W.: BSTJ 28 (1949) p. 608.

[6] Persson, K.B.: Phys. Rev. 106 (1957) p. 191.

[7] Margenau, H., Stillinger, D.: J. Appl. Phys. 30 (1959) p. 1385.

[8] Van der Ziel, A.: Noise. New York 1954.

[9] Bergmann, S.M.: IRE Transactions MTT-5 (1957) p. 237.

[10] Cobine, J.D.: Gaseous Conductors. New York. 1958.

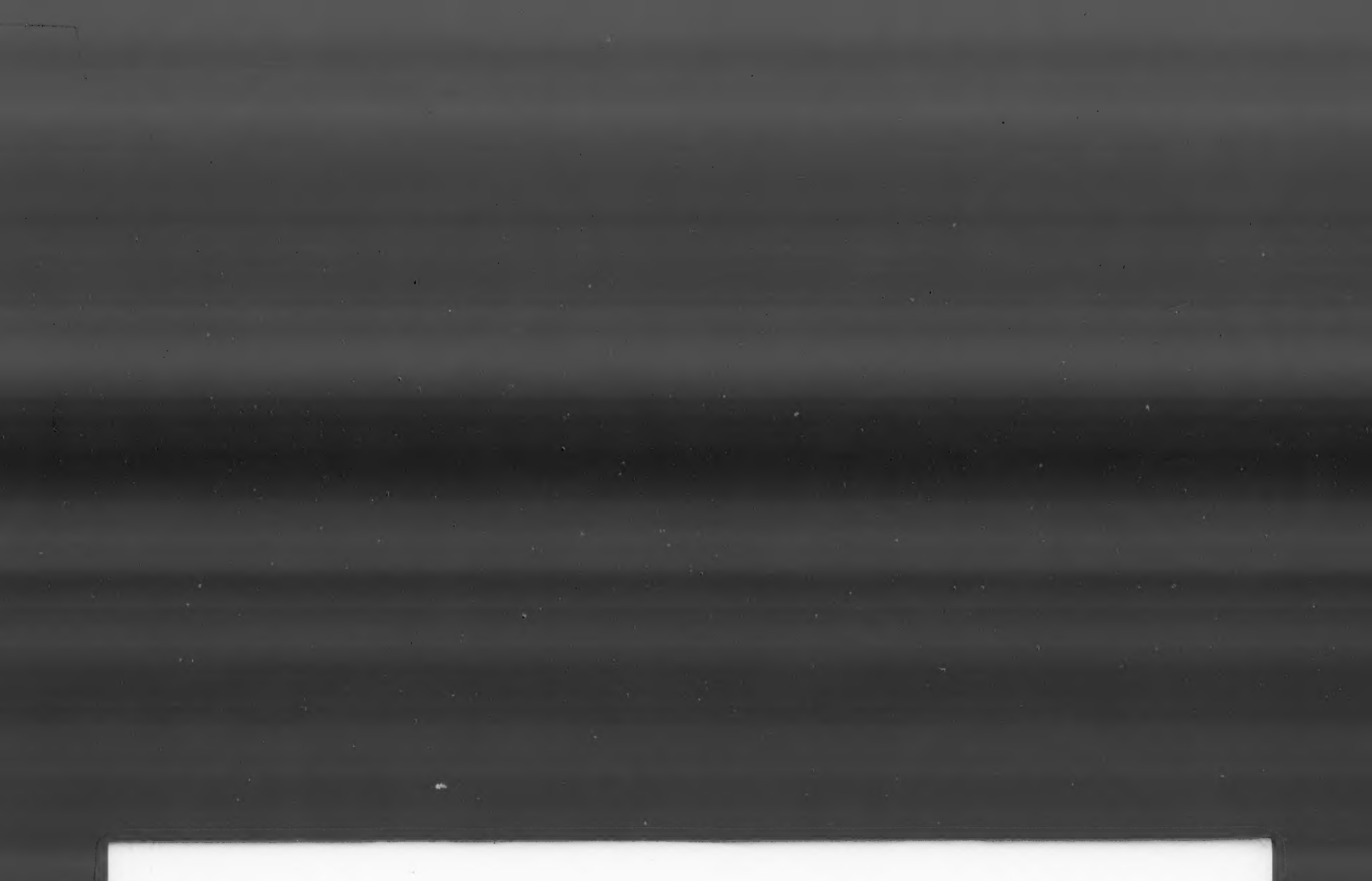
[11] Parzen, P., Goldstein, L.: Phys. Rev. 82 (1951) p. 724.

[12] Stark, L.: J. Appl. Phys. 25 (1954) p. 1155.

[13] White, W.D., Greene, J.G.: Proc. IRE 44 (1956) p. 939.

[14] Waymouth, J.F., Bitter, F.: J. Appl. Phys. 27 (1956) p. 911.

[15] Robertson, H.S.: Phys. Rev. 105 (1957) p. 368.



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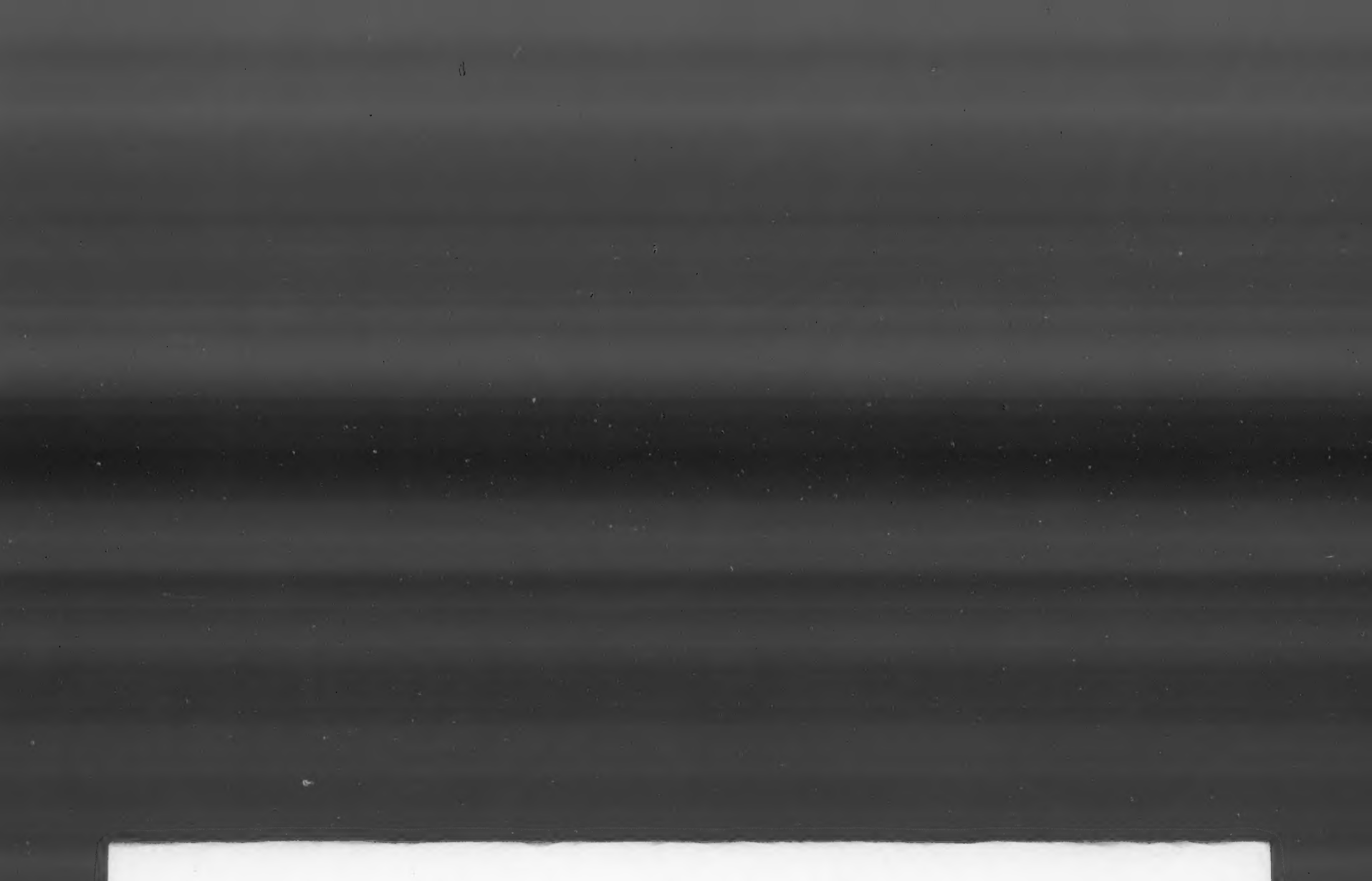
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